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Comparison of Proton, Neutron and Electron Radiation-Induced Electron Traps in N-GaAs Epilayers Studied by Deep Level Transient Spectroscopy

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL MEMORANDUM
DREO TM 1999-129
December 1999

National Defence Défense nationale

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Project
5EC11

ABSTRACT

This paper compares the deep level transient spectroscopy (DLTS) study of proton radiation-induced defects in molecular beam epitaxy (MBE) n-GaAs with that of the defects generated in n-GaAs by high energy electron and neutron radiation. For proton irradiation, it was found that the density of radiation-induced traps increased with radiation fluence. The activation energies, capture cross sections and trap densities with respect to radiation fluence are reported. Some of the observed traps have the same signatures as those reported previously for proton-irradiated vapour phase epitaxy (VPE) and liquid phase epitaxy (LPE) GaAs. The detailed structure of the trap previously designated as PR4 by Eisen *et al* [10] is also presented . This structure is observed for the first time as two distinct peaks in the DLTS spectra of proton-irradiated MBE n-GaAs corresponding to two bulk traps in GaAs film independent of their position within the film. The results are compared to previous studies of neutron and electron irradiated n-GaAs performed in our laboratory. The results indicate that some defect centres are generated by all three types of high energy particles discussed in this work, but that others are radiation-type dependent. The significance of the nature of the irradiating particle and the unirradiated GaAs in the growth of radiation-induced defects is identified.

RÉSUMÉ

Ce document compare l'étude de spectroscopie capacitive (DLTS) sur les défauts radio-induits des protons dans le n-GaAs épitaxie en faisceau moléculaire (MBE) avec les défauts généré dans le n-GaAs par des électrons et neutrons à haute énergie. Pour la radioexposition de protons, il a été prouvé que la densité des pièges radio-induits augmente avec la fluence du rayonnement. L'énergie d'activation, les sections efficaces capturées et la densités des pièges se rapportant à la fluence de rayonnement sont reportées. Certains des pièges observés ont la même signature que ceux établis antérieurement pour les protons radioexposés au GaAs épitaxie en phase vapeur (VPE) et liquide (LPE). La structure détaillée des pièges, désignée PR4 par Eisen et al[xxx], est aussi présentée. La structure est observé pour la première fois comme étant deux maximum distincts sur le spectra DLTS des protons radioexposés au n-GaAs MBE correspondant à deux pièges majeurs dans la pellicule de GaAs sans aucun lien avec leurs positions à l'intérieur de la pellicule. Les résultats sont comparés aux études faites auparavant par nos laboratoires sur les neutrons et électrons radioexposés au n-GaAs. Les résultats indiquent que certaines défectuosités sont générées par chacunes des trois types de particules à haute énergie qui font l'objet de ce travail, mais que d'autres sont dépendantes du type de radiation. La signification de la nature de la particule radioexposée et les propriétés du GaAs non-irradié dans le contexte de défectuosités radio-induites sont précisés.

EXECUTIVE SUMMARY

Nuclear radiation in the space environment is one of the leading factors limiting the life-span of a space mission. The semiconductor electronics of the spacecraft gets exposed to nuclear particles of varying energies. This radiation can cause permanent degradation of an electronic device due to damage created in the semiconductor material. Nuclear radiation can create a wide variety of lattice defects in the semiconductor by displacing atoms from their normal sites. This can have a catastrophic influence on the transport properties of the semiconductor. This paper deals with a comparative study of the main defects created by high energy protons (p), neutrons (n) and electrons (e) in GaAs thin films. It is shown that radiation-induced defect growth is influenced mainly by the type and energy of the radiation and also, to a lesser extent, by the nature of virgin GaAs material. This work can be used to estimate radiation damage to GaAs electronic systems in a space environment.

Khanna S.M., Yousefi G.H., Webb J.B., Wasilewski Z, Comparison of proton, neutron and electron radiation-induced electron traps in n-GaAs epilayers studied by deep level transient spectroscopy, Defence Research Establishment Ottawa, DREO TM 1999- 129, December 1999

SOMMAIRE

Le rayonnement nucléaire dans le milieu spatial est une des causes principales qui limite la durée de vie d'une mission spatiale. L'électronique des semiconducteurs est exposée aux particules nucléaires d'énergies variées. Cette radiation peut causer la détérioration permanente d'un dispositif électronique due aux dommages créés dans le matériau semiconducteur. Le rayonnement nucléaire peut créer une grande variété de défauts dans le semiconducteur en déplaçant les atomes de leur emplacement naturel. Ceci peut avoir une influence catastrophique sur les propriétés de transport du superconducteur. Ce document traite d'une étude comparative sur les principaux défauts créés par des protons (p), neutrons (n) et lectrons (e) à haute énergie dans une mince pellicule de GaAs. Il est démontré que la croissance de défectuosités radio-induites est influencée essentiellement par le type et l'énergie de la particule nucléaire et aussi par le niveau de perfection du matériau GaAs. Ce travail peut être employé pour estimer les dommages causés par rayonnement aux composantes électroniques GaAs dans un milieu spatial.

Khanna S.M., Yousefi G.H., Webb J.B., Wasilewski Z, Comparison par spectroscopie capacitive de pièges d'électron radio-induits de proton, neutron et électron dans une pellicule de n-GaAs, Le Centre de Recherche pour la Défense Ottawa, CDRO TM 1999-129, December 1999 (en anglais)

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1. INTRODUCTION

The study of radiation-induced defects in GaAs has received considerable attention[1-4] due to the interest in using GaAs electronic devices for space systems. This subject is equally important for understanding damage in GaAs during ion implantation used in device processing. Although the energy range and type of radiation used in these two fields are different, the nature of the principal defects induced by radiation could have substantial similarities.

It is well known that prolonged operation of a semiconductor device in the space environment can result in varying degrees of permanent degradation of device performance due to radiation damage created in the semiconductor material. In space, these devices get irradiated with a range of light and heavy nuclear particles over a wide energy spectrum. The study of dependence of radiation damage on the nature and energy of the radiating particle is important for several reasons. In particular, this could lead to prediction of radiation damage in these devices in any space radiation environment by limited radiation testing with a few types of particles only over a limited range of energies[5]. It has been shown recently that for a given particle, there is good correspondence between the growth of these defects and particle energy[6]. However, more work is needed particularly for the comparison of radiation damage due to different types of nuclear particles[6,7].

The effect of high energy particles, particularly electrons, on the generation of deep trapping levels in GaAs has been studied in some detail by a number of researchers[1-4]. In contrast, the effect of proton irradiation[8-11] has received considerably less attention, particularly on epilayers grown by the more advanced techniques of metalorganic vapour phase epitaxy (MOVPE) and molecular beam epitaxy (MBE). Proton radiation damage studies are particularly important for space applications and for light ion implantation work in device fabrication.

The only observation of proton radiation-induced defects in MBE n-GaAs has been by Eisen *et al*[10] who reported four electron traps designated as PR1 to PR4. This work is particularly significant since he compared these defects with the defects due to electron radiation on GaAs material from the same wafer, thus eliminating material dependent aspects of defect growth in their comparative study. Eisen *et al*[10] noted that the DLTS peak for the PR4 defect in their work was broad. From this observation and by studying DLTS spectra for GaAs at different distances within the material from the interface of the Schottky junction, they inferred that the DLTS peak for PR4 is made up of two peaks corresponding to two defects, PR4' and PR4". These two defects were however not observed simultaneously at any depth in the GaAs film. Comparing their results with prior work, Eisen *et al*[10] concluded that PR4" was a new defect. They measured the characteristics of this trap by studying the defects in GaAs film at different depths. These measurements were subject to the problems normally associated with non-uniform distribution of defects over the semiconductor thickness in the diode which lead to varying contributions to a given DLTS peak from constituent traps at different depths in the semiconductor. This problem has been eliminated in the present work.

The present paper details the DLTS study of proton-induced defects in MBE n-GaAs irradiated at room temperature by 10 MeV protons. At this energy, the radiation damage in a few

micron thick GaAs film is relatively more uniform than due to keV energy protons. Further, in contrast to prior work on radiation damage in GaAs with keV protons[8-10], the present work with higher energy proton radiation is more pertinent to space environment where proton energy could extend up to several hundreds of MeV. In contrast to the work of Eisen *et al* [10], six distinct trapping levels are observed. In particular, the defects PR4' and PR4" were observed simultaneously for the first time at any depth in the GaAs film in all proton-irradiated GaAs samples independent of the doping level. It would be expected that this work would provide more representative characteristic parameters for the defects in irradiated GaAs. The activation energies, capture cross sections and trap densities with respect to radiation fluence have been determined for these traps. These levels are compared with those reported previously for proton irradiation, by Eisen *et al*[10] in particular, and with our prior results for electron[12] and neutron[13] irradiated GaAs.

2. EXPERIMENTAL

The MBE samples which have been used in this study were grown on (001) semi-insulating Horizontal Bridgeman (HB) GaAs substrates with a V80H VG-Semicon MBE system. The GaAs layers were grown at a growth rate of 1 μm/hr at 600 C, as measured with a calibrated IR pyrometer. All layers were lightly silicon doped (1×10^{15} – $1 \times 10^{16} cm^{-3}$ doping range). The thickness of the films were in the range of 4 to 10 μm. Diode fabrication was performed by diffusing Sn balls through the epilayer surface to the heavily doped substrate to provide an ohmic contact. The epilayer was then degreased in vapour condensed chloroform and then weakly etched in an ammonium hydroxide vapour. Au/GaAs Schottky diodes were then fabricated by sputter-depositing gold through a stainless steel mask, using DC magnetron sputtering at an argon pressure of 30 mtorr. This pressure ensured a small mean free path for the sputtered gold atoms in the system, and a low (thermal) arrival energy at the GaAs surface. This was found to give very low interface defect densities and hence nearly ideal Schottky diode behaviour. The series resistance and I-V characteristics of all diodes were measured before and after irradiation. DLTS spectra were recorded over the temperature range of 80K to 450K with a Polaron 6400 DLTS system. Measurements were performed only on those diodes having a low series resistance and ideality factor $n < 1.1$. All samples were irradiated with 10 MeV protons at McMaster Univeristy, Canada over a fluence range of 0-5×10^{12} p/cm^2 at room temperature. DLTS spectra were taken before and after irradiation on each GaAs Schottky diode. All DLTS spectra were reproducible with no observable annealing effects over the measurement temperature range.

3. RESULTS

There is considerable variability in the nomenclature for radiation-induced defects in GaAs. To avoid confusion, we have adopted the nomenclature used by Eisen *et al* [10] and called the proton-induced defects as PR1 to PR4. For electron and neutron-induced defects, we have followed the nomenclature used in our prior work[12, 13] which is also similar to that used by Martin *et al*[3]. The neutron-induced defects have been further identified by attaching a suffix n for

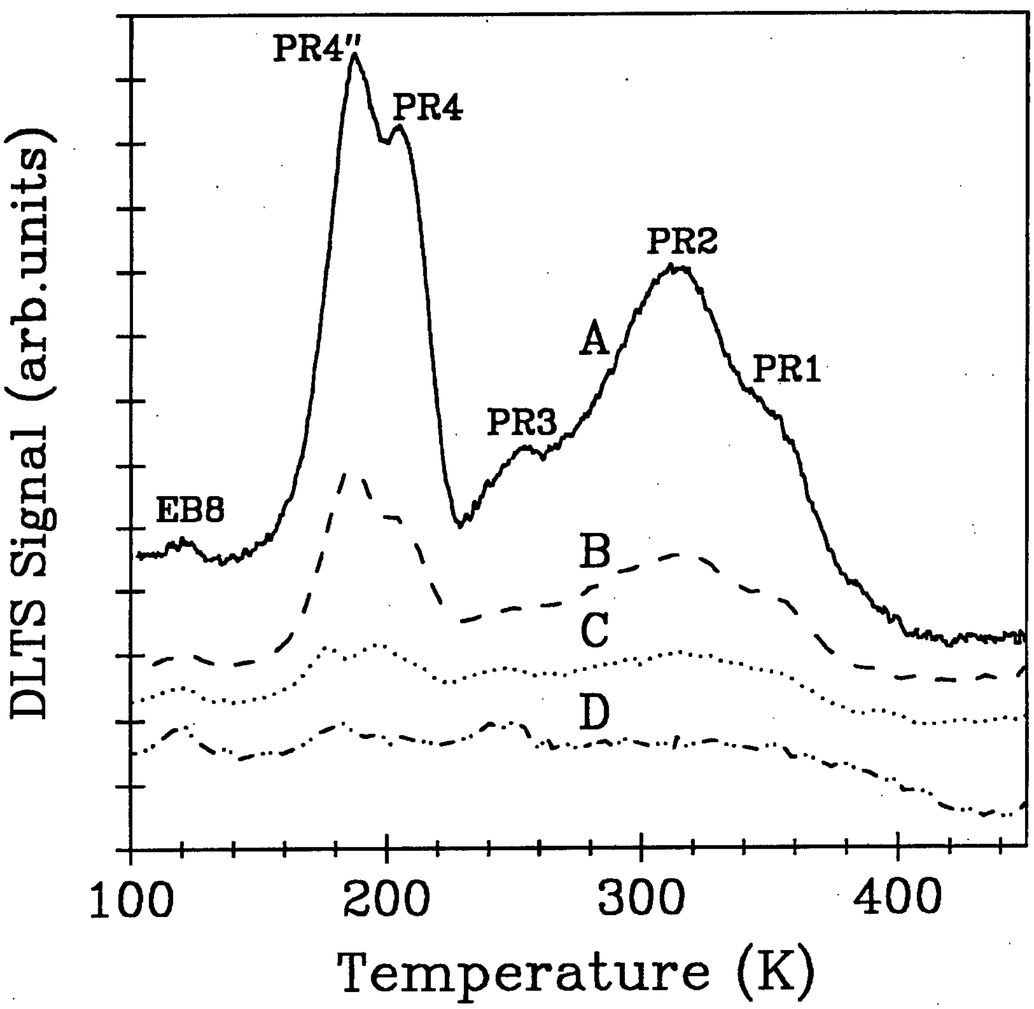


Fig.1 DLTS spectrum of MBE n-GaAs with background carrier density of 9×10^{15} cm^{-3} irradiated at different proton fluence levels. A: 5.3×10^{12} /cm^2 , B: 1.6×10^{12} /cm^2, C: 5.7×10^{11}/cm^2 , D: 1.6×10^{11} /cm^2

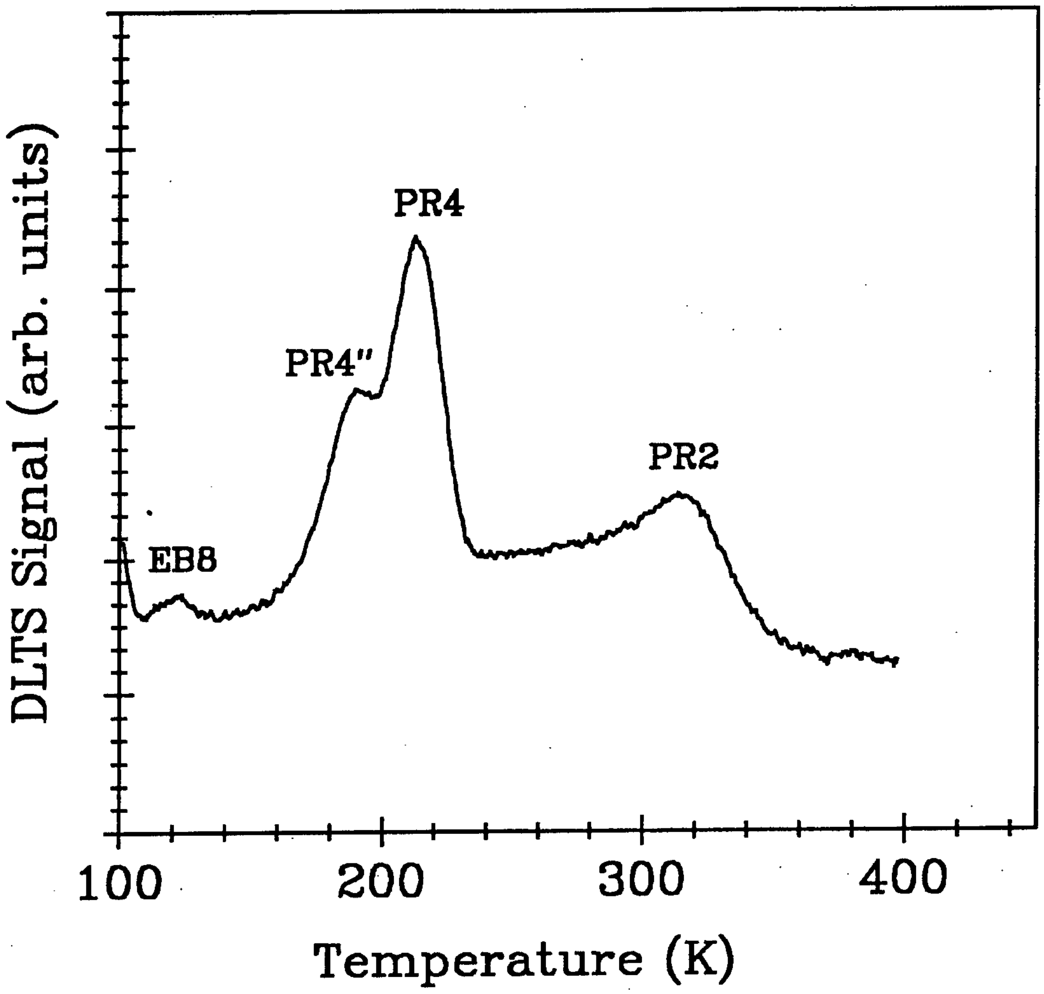


Fig.2 DLTS spectrum of MBE n-GaAs with background carrier density of 5×10^{14} cm^{-3} irradiated at $1.04 \times 10^{12}/cm^2$ proton fluence level.

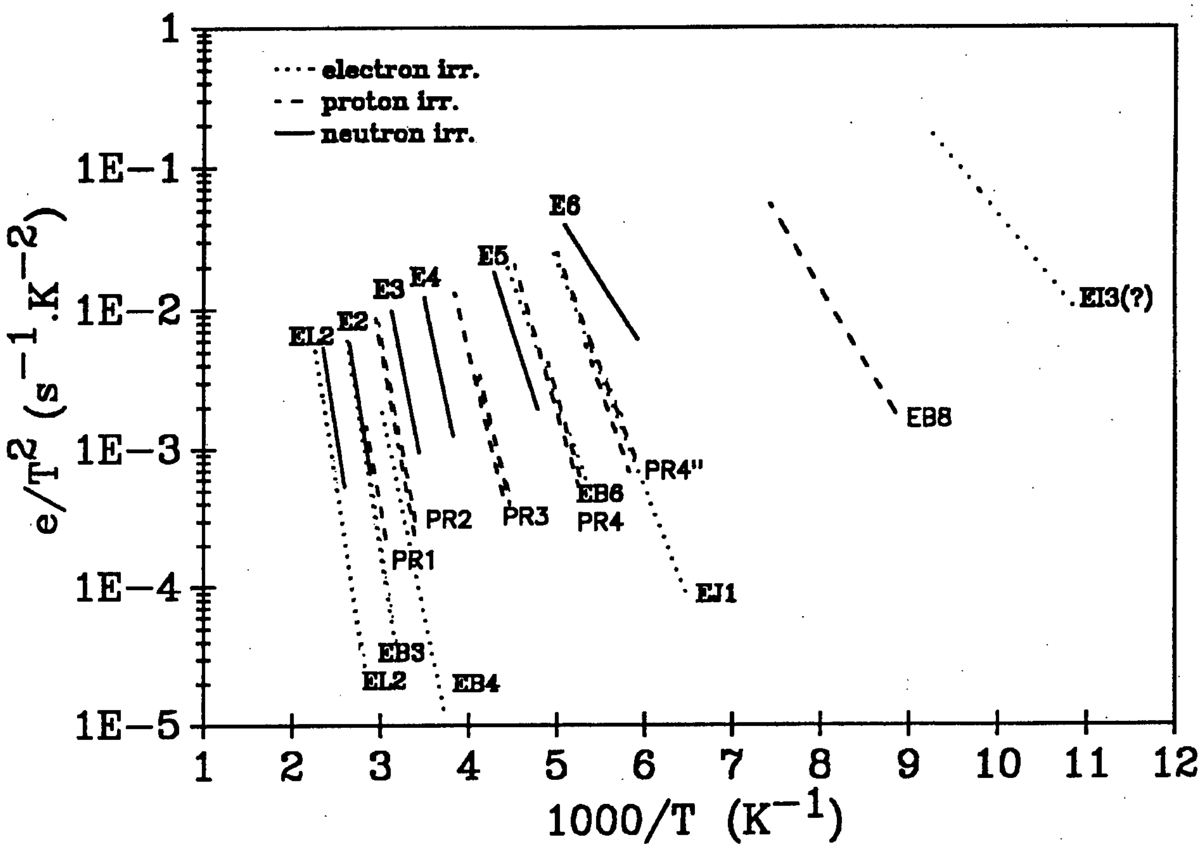


Fig.3 Emission rate versus reciprocal temperature for electron traps generated in n-GaAs by protons, neutrons and electrons.

neutrons to the defect name. Wherever possible, their correspondence with well-known radiation-induced defects has also been noted.

Figures 1 and 2 show the DLTS spectrum of electron traps in MBE n-GaAs samples doped at two different doping levels on irradiation with 10 MeV protons. Six distinct electron traps are clearly observed at the highest proton fluence for the material with doping level $n = 9 \times 10^{15}$ cm^{-3}, with five of these levels increasing in concentration as the irradiation dose is increased. For the material with $n = 5 \times 10^{14}$ cm^{-3}, only four of these levels are clearly observed.

Figure 3 gives a plot of (e/T^2), representing the thermal emission rate e divided by the square of the temperature T, versus reciprocal temperature for the levels shown in Figs.1 and 2. The calculated energy depths E and capture cross-sections σ which define the unique signatures for each of the traps have been calculated from the data shown in Figure 3 using the well known expression[3]

$$e\,(T) \;=\; \gamma\, T^2 (\sigma \exp(-\frac{E}{kT}))$$

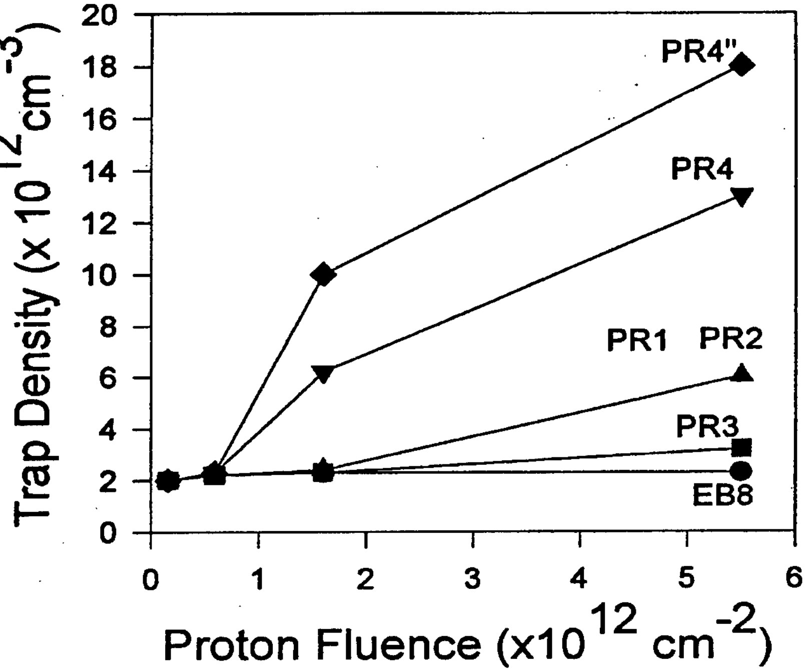
where the capture cross-section and trap depth are given by σ and E respectively. γ is a constant and is equal to 2.28×10^{20} $cm^{-2}s^{-1}K^{-2}$ for GaAs. These trap signatures are listed in Table I.

Also shown in the Table I are the reported values for defect characteristics from four prior studies of proton irradiated MBE, VPE and LPE GaAs [8-11] with the data from the present work. Following Ref. 10, the corresponding levels have been labelled as PRl to PR4". The additional electron trap observed in our work at ~120K was not seen by Eisen *et al* [10] , and has been labelled here as EB8 following Ref 3. This trap does not increase in density as the proton fluence increases. EB8 has been identified as a native defect in MBE grown GaAs [16,3]. Figure 4 shows the trap density vs. proton fluence for proton-induced traps in our two n-doped MBE samples.

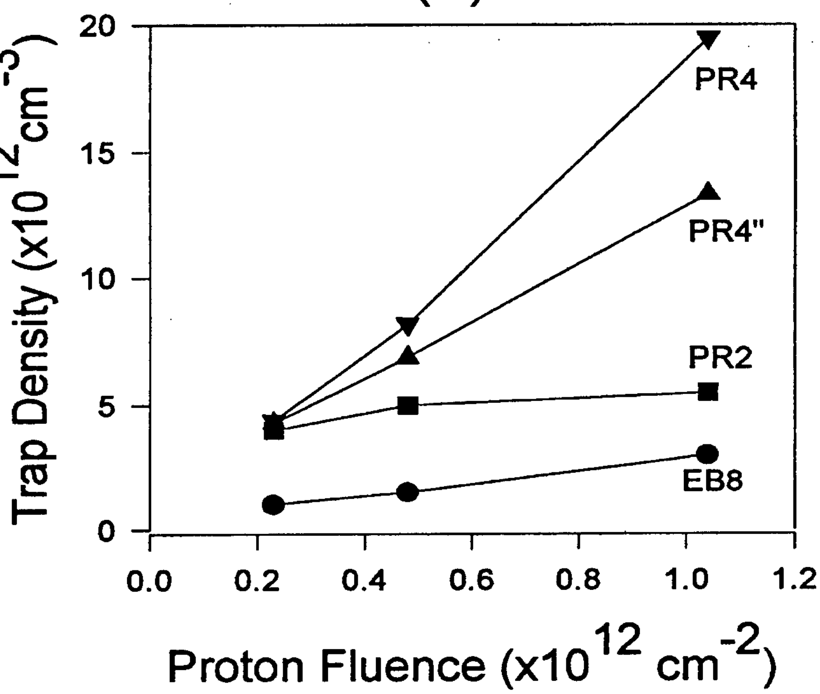
Finally Figs. 5(a), (b) and (c) show a comparison of the DLTS signals observed in electron[12], neutron[13] and proton irradiated GaAs in our samples. The electron and neutron studies were performed in our earlier work on MOVPE-grown GaAs (hence the observation of the EL2 level shown in Figs. 5(a) and (b) at ~400K). Plots of T^2/e for these levels are also shown in Fig. 3. The corresponding energy values and capture cross-sections of the levels are given in Table II.

4. DISCUSSION

Reviewing prior results on proton-induced defects in GaAs, we note that PR1, PR2 and PR4 are the principal defects observed in the DLTS spectra for different types of GaAs over 100-400 K temperature range. As discussed below, additional defects have been reported on annealing the irradiated material or on studying the DLTS spectra at different depths in GaAs



(A)



(B)

Fig.4 Trap density in proton-radiated MBE n-GaAs vs. proton fluence for two doping levels: (a) $9 \times 10^{15}/\mathrm{cm}^3$, (b) $5 \times 10^{14}/\mathrm{cm}^3$.

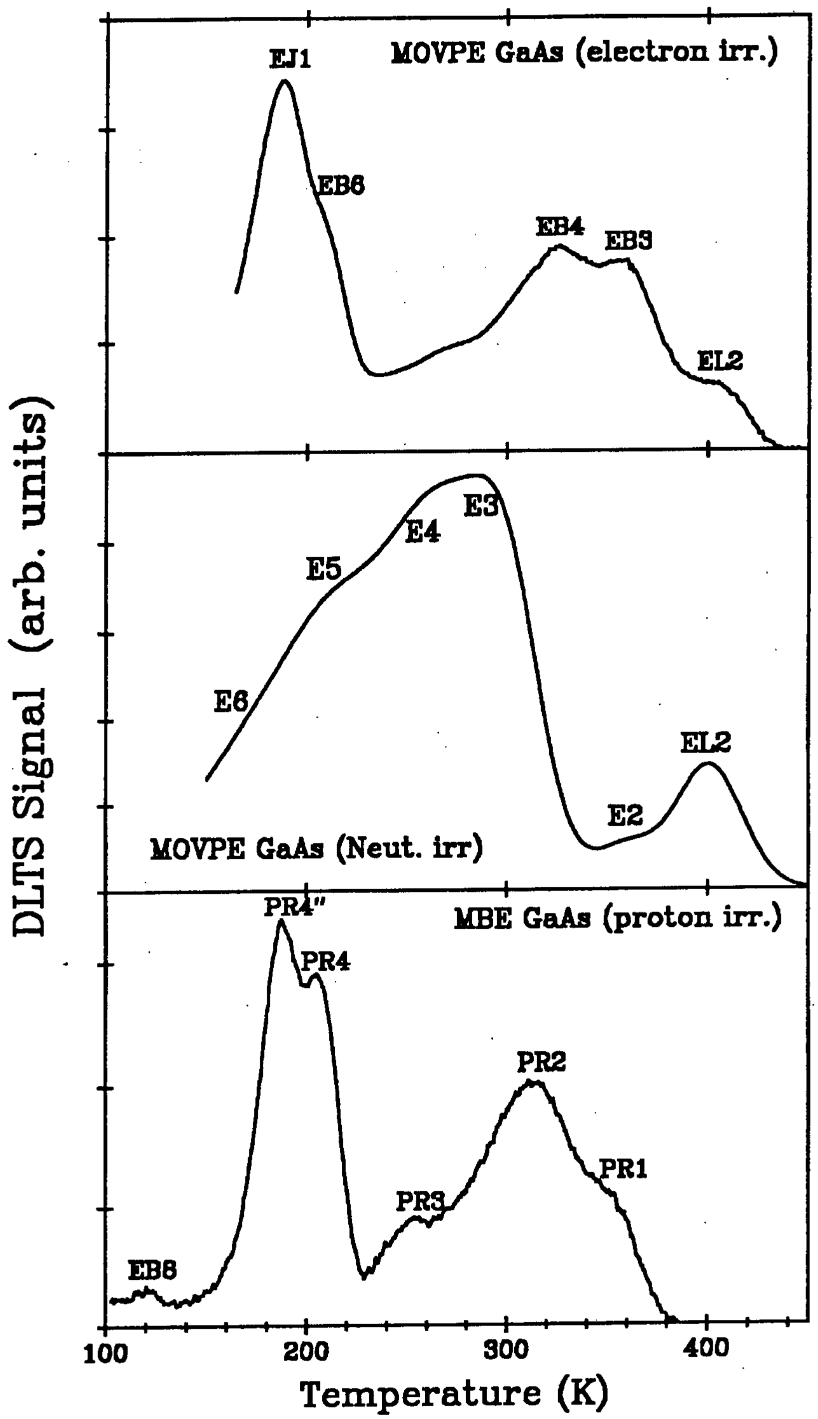


Fig.5 Comparison of DLTS signals observed for (a) electron, (b) neutron and (c) proton irradiated GaAs.

TABLE 1: Trap energies and capture cross-sections for proton irradiated n-GaAs.

(*) indicates radiation-induced traps. EL2 is a native defect in MOVPE GaAs[3] while EB8 is a native defect in MBE GaAs[3].

	MBE[10]		LPE[8]		VPE9		LPE[11]		MBE [present work]	
Trap	E (eV)	σ (cm^2)	E (eV)	σ (cm^2)	E (eV)	σ (cm^2)	E (eV)	σ (cm^2)	E (eV)±0.02	σ (cm^2)
*PR1	0.79	2.4×10^{-12}	0.71	4.2×10^{-13}	0.85	8×10^{-12}	0.82	1.6×10^{-13}	0.71	1.6×10^{-12}
*PR2	0.59	8.2×10^{-15}	0.52	6.6×10^{-14}	0.65	6.8×10^{-14}	0.61	2.4×10^{-14}	0.62	9.1×10^{-15}
*PR3	0.40	1.9×10^{-15}							0.39	2.0×10^{-14}
*PR4'	0.33	5.7×10^{-15}	0.39	6×10^{-15}	0.33	3×10^{-15}	0.33	2×10^{-15}	0.32	8.2×10^{-15}
*PR4"	0.34	4.3×10^{-14}	0.3		0.3	3×10^{-14}			0.37	5.1×10^{-14}
EB8									0.21	2.0×10^{-14}
EL2							0.76	1.2×10^{-14}		

Table II: Energies and capture cross sections for radiation-induced traps in GaAs due to electron radiation[12], neutron radiation[13] and proton radiation in our samples. Data on proton induced traps is from the present work.

Trap Name (type of radiation)	E(eV)	σ (cm^2)	Comments
EB3 ; (electron)	0.82	1.6×10^{-12}	Also denoted as E5'
$E2_n$; (neutron)	0.79	9.3×10^{-13}	EB3 = $E2_n$ = PR1
PR1 ; (proton)	0.71	1.6×10^{-12}	
EB4 ; (electron)	0.63	1.4×10^{-14}	Also denoted as E4[1]
$E3_n$; (neutron)	0.65	7.5×10^{-13}	EB4 = PR2
PR2 ; (proton)	0.62	9.1×10^{-15}	
EB6 ; (electron)	0.36	1.7×10^{-15}	Also denoted as E3'
$E5_n$; (neutron)	0.39	1.7×10^{-14}	EB6 = PR4 = $E5_n$
PR4'; (proton)	0.32	8.2×10^{-15}	
EJ1 ; (electron)	0.32	1.0×10^{-14}	EJ1 = EB7(?)[3] = PR4"
PR4";(proton)	0.37	5.1×10^{-14}	
PR3 ; (proton)	0.39	2.0×10^{-14}	Also seen in electron irradiated material[12], but has not been characterized.

from the Schottky metal/semiconductor interface. Defects observed below 80 K by other workers have not been included here as they are outside the scope of the present work. We will discuss our results in light of the published data. In particular, Eisen *et al*[10] have concluded that the PR4" defect observed in their work was a new defect and had not been reported earlier in GaAs independent of the material growth process and type of radiation. A common problem of non-uniform radiation damage across the film thickness is noted in most of the prior DLTS studies on proton-induced damage in GaAs which could be a factor in inhibiting uniform growth and observation of PR4" in previous results. This limitation has been eliminated in the present work.

4.1 Electron Traps PR1 to PR4"

Li *et al*[8] carried out DLTS measurements on LPE n-GaAs (Sn doped at 2 - 8 $\times 10^{16}$ cm^{-3}) irradiated with 200 keV protons. They observed three distinct electron traps in irradiated samples that correspond to PR1, PR2 and PR4. In addition, they observed a defect at ~ 100K. The level PR4 observed at low temperature (~180K, E = 0.31 eV) was observed to split upon annealing into two levels with energies of E = 0.3 and 0.39 eV and with a temperature difference of ~ 31 K between the two corresponding DLTS peaks. Similarly, Guillot *et al*[9] studied damage in VPE n-GaAs doped at 2×10^{16} cm^{-3} on irradiation with 100keV protons. They observed traps which correspond to PR1, PR2, PR4 and an additional electron trap D1 in the DLTS spectra of the irradiated material over the same temperature range. The signatures for PR4 and D1 and the temperature difference between their corresponding DLTS peaks are similar to the corresponding defects observed by Li *et al*[8] after annealing. In addition, Guillot *et al* [9] also observed a low-density defect below 100K.

Brunkov *et al*[11] reported four electron traps in LPE grown n-GaAs (n-doped at 2×10^{15} cm^{-3}) after 6.7 MeV proton irradiation. Three of these traps can be assigned to PR1, PR2 and PR4 however the fourth trap was attributed to the arsenic antisite defect EL2. We will discuss EL2 later in this work. Unlike Guillot *et al*[9], Brunkov *et al*[11] did not observe another defect below the peak temperature for PR4.

Recently, Eisen *et al*[10] have conducted a comprehensive study of defects in MBE n-GaAs (doping levels: 2.5×10^{16} cm^{-3} and 1×10^{17} cm^{-3}) irradiated with 50 keV protons and compared them to defects due to 1 MeV electron radiation in similar samples taken from the same wafer. They compared in detail their results on proton-induced damage with prior work. As pointed out earlier, Eisen *et al*[10] reported the observation of four electron traps. The PR4 DLTS peak observed at ~180 K showed considerable broadening, and it was inferred that this peak was composed of two overlapping peaks which were labelled as PR4' and PR4".

In contrast to the above results, we observe PR4' and PR4" clearly as two separate peaks in the DLTS results for irradiated GaAs at all fluence levels used in our work independent of the bias voltage and hence at all depths in the GaAs film. Similar results were observed for GaAs samples doped at two doping levels (see Figs. 1 and 2). The trap density of PR4" is higher than that of PR4' at the higher doping level (n $=9\times10^{15}$ cm^{-3}), while the reverse is true for the less

doped GaAs sample. The defect PR3 was observed in the higher doped GaAs sample only. Further, for the higher doped GaAs, the trap density of PR2 is greater than that for PR1. For less doped sample, the defects PR3 and PR1 are non- existent. EB8 is observed at ~ 120K in both of these samples.

Eisen *et al*[10] have concluded that the defect PR4' was the same as the electron generated trap E3' (labelled as EB6 in our study[12]). Further, they also concluded that the defect PR4" was a new defect which had not been observed earlier in GaAs. In the following, we discuss the defects PR4' and PR4".

The present results are in agreement with the above-noted assignment for PR4'. Furthermore our results suggest that the neutron generated trap $E5_n$[13] may also result from the same defect. PR4' and PR4" traps were not resolved in the results of Eisen *et al*[10] for any region of GaAs film. They were however able to determine the signature of these traps, albeit at different depths in GaAs film through suitable choices of bias voltage. Thus, while the two traps PR4' and PR4" were never observed simultaneously, they could study them by arranging different contributions from these traps to the resultant single DLTS peak. The temperature difference in the DLTS peaks for these two traps in their work, although not at the same depth in the film, was ~12K. Although they had observed that PR4' annealed more rapidly than PR4", they did not observe splitting of the PR4 peak on annealing as seen by Li *et al*[8]. Thus, even on annealing, the DLTS peak for PR4 did not split into two peaks corresponding to PR4' and PR4" defects for any region of the film.

It is clear that the density of the various defects in the results of Eisen *et al*[10] and possibly other works also[8,9] was not uniform across the film thickness and different defects contribute to varying extent to the resultant peak in the DLTS spectra at any depth in the film. Eisen *et al*[10] have pointed out the depth dependence of PR4' and PR4" in their results. This problem is further aggravated in their work with heavier ion irradiation. Thus, PR4" dominated in the resultant peak PR4 in the case of irradiation with helium and carbon ions. In GaAs, the ranges of 50 keV protons, 200 keV protons, 150 keV helium ions and 300 keV carbon ions are ~ 0.4 μm, 1.5 μm, 0.6 μm, and 0.5μm respectively. In contrast, the range of 10 MeV protons in GaAs used in the present work is 427 μm. The typical value for the film thickness probed in most DLTS studies range up to a few microns. Thus, similar to the results of Eisen *el al*[10], even 100-200 keV proton irradiation used by Guillot *et al*[9] and Li *et al*[8] would lead to non-uniform damage in GaAs films while with 10 MeV protons, the damage would be relatively uniform over several μm thick film.

Eisen *et al*[10] have observed the dominance of PR4" peak in GaAs irradiated with heavier ions (carbon or helium ion) and also, in proton irradiated GaAs Schottky junctions at lower bias voltages. This indicates that PR4" in their work is located close to the junction interface and PR4' is located in the bulk of the GaAs film. In contrast, in the present work, PR4' and PR4" are observed simultaneously at all distances from the Schottky junction interface in the GaAs film. It was checked in our work that PR4' and PR4" are bulk traps and the results are independent of the depth in the GaAs film at which these measurements are taken. The temperature difference in DLTS peaks corresponding to these two traps is ~18K in our results.

Eisen *et al*[10] have concluded that PR4" was not the same trap as D1, as designated by Guillot *et al*[9]. Further, on comparing the radiation-induced defects in their samples grown with MBE process and the wafers grown with liquid-encapsulated Czochralski method, Eisen *et al*[10] concluded that the growth of PR4" defect is independent of the material properties. Our results confirm both of these conclusions. Using MBE GaAs thin films with different doping levels, we find that the signature of PR4" is independent of the material property. In addition, we also note that the temperature difference between the DLTS peaks corresponding to PR4' and PR4" in our measurements is ~18K as compared to ~12 K in the results of Eisen *et al*[10]. These values are much lower than ~31 K, the temperature difference between the DLTS peaks for E3 (PR4) and D1 in the results of Guillot *et al*[9], thus further confirming that D1 and PR4" defects are not the same. However, in contrast to the conclusion of Eisen *et al*[10] that PR4" trap had not been observed in GaAs earlier, we note from the results in Fig. 5 and Table II that PR4" and the electron radiation-induced trap EJ1[12] observed in our previous work may result from the same trap. This is further supported by the fact that the temperature difference between the DLTS peaks for EJ1[12] and EB6[12] for electron irradiated MOVPE GaAs is also ~18K similar to the temperature difference between the peaks for PR4' and PR4" in our present measurements.

Figures 4a and 4b give the trap density of the various defects in MBE GaAs at two doping levels as a function of the fluence. These results indicate that the density of defects is linearly dependent on fluence over a limited, low fluence range only. At a higher fluence level which varies with the defect, the defect density increases non-linearly with fluence. In contrast to the higher doped GaAs sample, we note that PR1 and PR3 traps are not present in GaAs doped at 5×10^{14} cm^{-3} and PR2 is the most dominant trap in that temperature range. Further, the relative densities of the traps PR4' and PR4" are reversed between the low and high doped GaAs samples. The introduction rate for PR4' and PR4" is higher in the less-doped GaAs sample.

The electron traps designated PR1 and PR2 can also be directly associated with the electron traps EB3[12] (or E5[1]) and EB4[12] (or E4[1]) respectively, generated by electron irradiation, and possibly traps $E2_n$[13] and $E3_n$[13] generated by neutron irradiation [see Table II and Figs. 3 and 5]. Eisen *et al*[10] concluded that PR2 and EB4 arose from the same defect. However, based on annealing behaviour, they also concluded that PR1 was not the same as EB3(E5) even though the trap signature given in their report for PR1 matches closely the signatures determined in this and previous studies for EB3.

Finally Eisen *et al*[10] were not able to correlate PR3 with any of the peaks observed in prior work on electron irradiated GaAs. In fact this peak was not observed in their electron irradiated MBE layers. However, the present results indicate that PR3 matches the peak observed in our electron irradiated MOVPE GaAs[12] although the signature for this peak was not determined in the latter case since it was masked at some rate windows by the stronger EB3 and EB4 peaks (see Fig. 5(a)). Further, they had concluded that the occurrence of PR3 was dependent on the properties of the sample material. We also observe the dependence of growth of PR3 on GaAs sample properties in the present work. Thus, PR3 was observed in GaAs sample doped at 9×10^{15} cm^{-3} but not in the sample doped at 5×10^{14} cm^{-3}. It is possible that the increased trap density of PR4, and particularly of PR4' in less doped GaAs sample for the same fluence irradiation level may be related to the lack of growth of PR3 in those GaAs samples.

Finally, no EL2 was observed before or after proton irradiation in the present work. This must be related to the process of film growth. An increase in EL2 trap density has been noted in neutron-irradiated MOVPE GaAs by Jorio *et al*[14] and in proton-irradiated[11] LPE GaAs by Carlone[15] respectively.

5. CONCLUSION

We have studied radiation-induced defects due to 10 MeV proton radiation in MBE n-GaAs thin films doped at two doping levels. In contrast to the prior works with keV energy range proton irradiation[8-10], 10 MeV proton radiation leads to a more uniform damage in several μm thick GaAs films. Thus, in the present work, PR4' and PR4" defects were observed simultaneously for the first time as two distinct peaks in the DLTS spectra at any depth in the semiconductor film. The densities and characteristics of these bulk traps were found to be independent of their position within the GaAs film. We confirm most of the conclusions of Eisen *et al*[10] regarding proton-induced defects in GaAs. Most of these radiation-induced defects in GaAs films are common to proton, neutron and electron radiations. However, the relative densities of these defects could be highly dependent on the nature of radiation. In addition, there are some defects whose origin is radiation-type dependent. Further, contrary to the conclusions of Eisen *et al*[10], there are indications that PR4" and PR3 traps are not exclusive to proton radiation, but are induced by electron radiation also. These traps have been reported in our earlier works[12,13].

It may be presumed naively that radiation damage in a semiconductor is controlled mainly by the atoms of the host lattice and the crystal structure. Other factors such as the defects in the unirradiated material and doping level may naively be considered to have marginal effects only on the radiation-induced traps. In contrast, this work shows that the nature of radiation-induced defects depend strongly on (i) the type of radiating nuclear particle, (ii) doping level, and (iii) properties of the unirradiated GaAs semiconductor. It is true that most of the defects are produced in all types of GaAs material independent of the nature of the radiation particle. However, the detailed nature and relative densities of these defects are noticeably influenced by the material growth process, doping level and type of radiation. In particular, there are differences in the induced defects due to heavy particles, such as protons and neutron, and those due to electrons or gamma ray irradiations. Electrons and gamma rays typically induce simple defects while heavier particles tend to generate complex defects. There are noticeable differences between the damage due to protons and neutrons also. Further, it is possible to estimate damage due to one type of particle, especially protons, at different energies by measuring damage due to that particle at a few energies[5,6]. However, correlation of radiation damage between different types of particles such as protons, neutrons, electrons and gamma rays would have to be tested and confirmed by radiation testing with these particles over a range of energies[5-7].

6. ACKNOWLEDGEMENT

We would like to thank Chris Holmes for assisting in analyzing the data.

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Comparison of Proton, Neutron and Electron Radiation-Induced Electron Traps in N-GaAs Epilayers Studied by Deep Level Transient Spectroscopy (U)

4. AUTHORS (Last name, first name, middle initial)

Khanna, Shyam M., Yousefi, G.H., Webb, Jim, and Wasilewski, Z

5. DATE OF PUBLICATION (month and year of publication of document)

December 1999

6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)

15

6b. NO. OF REFS (total cited in document)

15

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

DREO Technical Memorandum

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

Space Systems and Technology Section
Defence Research Establishment Ottawa,
Ottawa, Ontario, K1A 0Z4

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)

5EC11

9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)

10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)

DREO Technical Memorandum # TM1999-129

10b. OTHER DOCUMENT NOS. (Any other numbers which may be assigned this document either by the originator or by the sponsor)

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This paper compares the deep level transient spectroscopy (DLTS) study of proton radiation- induced defects in molecular beam epitaxy (MBE) n-GaAs with the defects generated in n-GaAs by high energy electron and neutron radiation. For proton irradiation, it was found that the density of radiation-induced traps increased with radiation fluence. The activation energies, capture cross sections and trap densities with respect to radiation fluence are reported. Some of the observed traps have the same signatures as those reported previously for proton irradiated vapour phase epitaxy (VPE) and liquid phase epitaxy (LPE) GaAs. The detailed structure of the trap previously designated as PR4 by Eisen et al is also presented . This structure is observed for the first time as two distinct peaks in the DLTS spectra of proton- irradiated MBE n-GaAs corresponding to two bulk traps in GaAs film independent of their position within the film. The results are compared to previous studies of neutron and electron irradiated n-GaAs performed in our laboratory. The results indicate that some defect centres are generated by all three types of high energy particles discussed in this work, but that others are radiation-type dependent. The significance of the nature of the irradiating particle and the unirradiated GaAs in the growth of radiation-induced defects is pointed out.

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